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Reliable copper and aluminum connections for high power applications in electromobility

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Abstract

Investigations concerning the growth of intermetallic phases during the heat input both at the diffusion annealing of copper aluminum roll claddings and the subsequent welding process of copper-aluminum connections by using roll cladded inserts are compared to the analytical determination of phase growth. The temperature distribution in the cladding interface has been determined by thermal simulation, in order to calculate the growth of the intermetallic phases. A comparison between the width of the phases in the analytical calculation and the experiment is achieved. In consideration of high welding speeds, the energy input during the welding process is appraised in order to grade the growth of intermetallic phases. Furthermore the prevention of damage in the roll cladding interface by means of unadapted material thicknesses or welding parameters can be assessed analytically and numerically. The numerical simulations can determine the critical thickness of the roll cladding to avoid damage like exceeding growth of intermetallic phases.

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Keywords: copper; aluminum; roll cladding; laser welding; heat conduction; diffusion; power electronics

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1. Motivation / State of the Art

Due to its excellent electrical conductivity and high mechanical strength, copper alloys are established as standard materials for electrical systems. However, the increasing price of copper as well as its high density induces the demand for substitution with aluminum [1], especially in the background for realising economically lightweight structures (e.g. aluminum wiring loom) and cost-efficiency. Based on electrical properties, a complete substitution of all copper components like windings and spools by aluminum cannot be established. This requires the development of reliable connections of copper and aluminum. Welding provides high strength, low electrical resistance and long-term stability, which is needed for high power applications and energy storage. As it is shown in [2], a direct substance conclusive connection of copper and aluminum leads to irrepressible intermetallic phases due to a low metallurgical solubility. Most of these phases exhibit high hardness and come along with brittleness, which lead to failure of the dissimilar joint [3]. As shown in [4] a roll cladded interface allows splitting the dissimilar joint into two similar joints in order to significantly reduce and control the intermetallic phase formation. As it can be seen in Figure 1, a roll cladded insert can provide a copper-copper weld and an aluminum-aluminum weld.

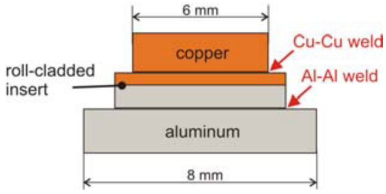

Fig. 1. Geometrical arrangement for laser welding of copper and aluminum connections with roll cladded inserts for applications in the electronic industrie [4].

Due to the substitution of copper by aluminum in electrical components and simultaneously providing of similar electrical and mechanical properties, aluminum parts have to feature a geometrical compensation of its lower electrical conductivity and tensile strength. This leads to an increased thickness (70 %), to achieve the electrical conductivity of copper.

Roll cladded inserts feature intermetallic phases with a thickness of about 1 µm to 20 µm in dependence of component thickness and furnace procedure. According to [5], at elevated temperatures, brittleness and electrical transition resistance rapidly increase with simultaneous growth of intermetallic phases. [6] postulates, that the general growth of intermetallic layers at copper-aluminum systems depending on the temperature rises significantly at temperatures higher $0.7 * T_s$ [6]. The diffusivity of matrix and substitution atoms is temperature dependant, because at every existing temperature in the atomic lattice, the equilibrium with a defined concentration of lattice vacancy is existent, which rises at higher temperatures [7]. Furthermore, the diffusivity is limited by the ability of the element absorption of the mating part [3]. In dependence of the exposure time, the increase respectively the decline of the dissimilar material concentration in the joining interface is based on the volume diffusion, which results in the formation of intermetallic phases [8]. Hence, the thermal input during welding into the interface has to be limited with the objective of gaining less growth of intermetallic phases. Heat input can be controlled easily by increasing the distance from welding to cladding interface with the aid of thicker claddings but is an oppositional proceeding concerning lightweight, leads to the development of an optimal cladding thickness. As it can be seen in Figure 1, the joining geometry for both welds is a fillet weld, which has to be performed in deep penetration mode in order to ensure sufficient cross section for low electrical resistance. To avoid melting of aluminum in the Al-Cu-interface with accompanied elevated diffusion of aluminum and copper, temperature has to be limited to < 660 °C by adapting the thickness of the roll cladding. For calculating the temperature distribution in this zone, a numerical simulation was performed. This distribution is used as input parameter for an analytical calculation of diffusion and enlargement of intermetallic phases by parabolic law (1). According to the parabolic law of [9], the intermetallic phase thickness x is calculated with the absolute term K for the growing rate and t is the process time.

$$x = \sqrt{K * t} \tag{1}$$

The growing rate K can be calculated by (2) with an initial rate k_0, the activation energy of phase growth Q, the molar gas constant R and the temperature T [10].

$$K = k_0 * \exp\left(-\frac{Q}{R*T}\right) \tag{2}$$

The equations (1) and (2) can be used for calculation of the thickness of each intermetallic phase (γ_2, δ, ζ_2, η_2 and θ) as long as solid state of both materials is existent. In the present case the total thickness of all intermetallic phases is of interest. For calculation of each phase, the parameters needed in (2) are listed in Table 2.

Table 1. Start initial rate k_0 and activation energy Q for all five intermetallic phases [10].

Phase	Start rate k_0 [cm^2/s]	Activation Energy Q [cal/mol]
γ_2	$3{,}2*10^{-2}$	31600
δ	$2{,}6*10^{-1}$	33500
ζ_2	$2{,}7*10^{6}$	61200
η_2	$1{,}7*10^{-6}$	19600
θ	$9{,}1*10^{-3}$	29300

Based on a numerical simulation to determine the temperature distribution in cladding interface, the growth of intermetallic phases is calculated analytically and compared both to raw roll claddings from the supplier and after welding experiments. The overall objective is to create a numerical model supported by analytical calculations for dimensioning the roll cladding in dependence of the thermal energy input during welding without inducing a massive growth of intermetallic phase layer. An important challenge is to minimize the amount of material thickness compared to the necessary connection area for mechanical and electrical requirements, preventing a thermal damage in the cladding interface.

2. Experimental Setup

For the welding samples, a disc laser featuring a wavelength of 1,030 nm, a maximum power of 4 kW and a spot diameter of 300 µm is used. The irradiation angle in the experiment and the simulation was 7° to the surface of the samples, in order to maximize the joint surface in the joining gap. Furthermore the roll cladding, made of pure aluminum (Al99.5) and pure copper (Cu-PHC) is welded in a similar material connection to avoid the formation of intermetallic phases. Using different relevant thicknesses (1 mm and 3 mm) of the roll cladding, in order to vary the thermal energy input into the cladding interface, the resulting expansion and shape of the melt pool shall be visualized by cross sections. In order to assure technical zero gaps between the two joining parts in the contact plane, the front faces are milled perpendicular to the surface. To avoid the influence of atmospheric gases on the surface of the melting pool, a shielding gas consisting of 76 % argon, 22 % helium and 2 % oxygen was used in a rate of 15 l/min, wherein the oxygen creates an oxide layer on the melting bath surface. Especially at high reflective materials, the induced metal oxide improves the absorption of infrared wavelength [11].

In order to appraise temperature in the roll cladding during laser beam welding, finite element simulation of the welding processes is conducted in COMSOL Multiphysics®. To confirm the results of numerical simulations, experiments of the heat conduction with identical material and welding parameters have been adduced. Fig. 2 shows the model for the thermal simulation. Because of deep penetration welding, the absorption of the infrared laser wavelength was adapted to 55 % in order to reach similar temperature distributions in dependence to the weld seam shape in the cross section of the experiment.

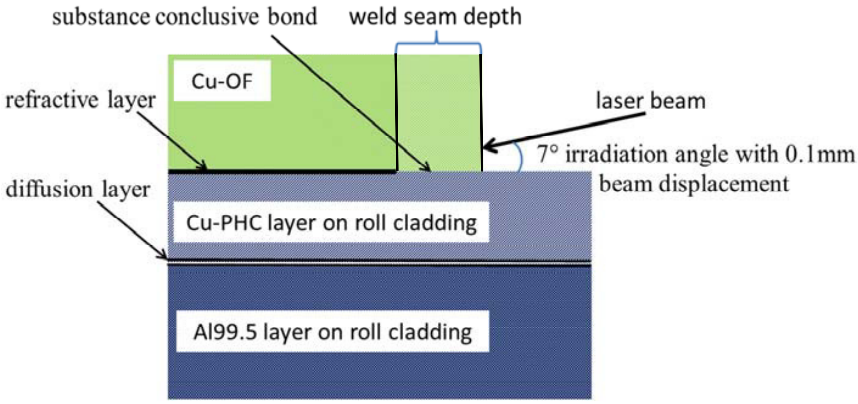

Fig. 2. Schematic description of simulation model.

The simulation does not include phase transformation, which means that no melt flow can be simulated. To model a joining gap of about 10 µm, a layer with thermal conductivity of air between the surface of the copper sided roll cladding and the bottom side of the copper sample was implemented. In order to assume the cross section of the weld seam, a virtual connection in joint area is implemented, so that it is similar to the experiment. The influence of shielding gas is neglected, but a general integrated convective cooling of the components (20 °C room temperature) is considered in the simulation. The physical properties of both materials, copper and aluminum, used in the numerical calculations are listed in Table 2 [12],[13].

Table 2. Important properties for the simulation model of copper and aluminum.

Property	**Al99,5** [12]	**Cu-OF** [13].
Density [g/cm³]	2.7	8.94
Melting point [°C]	660	1083
Tensile strength [N/mm²]	150	290
Electrical conductivity [10^6 S/m]	34	58
Thermal conductivity [W/m*K]	210	393
Thermal expansion [10^{-6}/m]	23.5	17

3. Results and Discussion

The first growth of intermetallic phases in the supplied roll claddings happens in the continuous annealing furnace process during 35 minutes at 480 °C directly after rolling of the two panel sheets. Based on furnace parameters during manufacturing, the growth of intermetallic layers (γ_2, δ, ζ_2, η_2 and θ) is calculated analytically with formulas (1) and (2) where the total layer thickness reaches 9.6 µm. Figure 3 shows the total intermetallic layer thickness depending on processing time and temperature, wherein the present furnace parameters are indicated by straight lines.

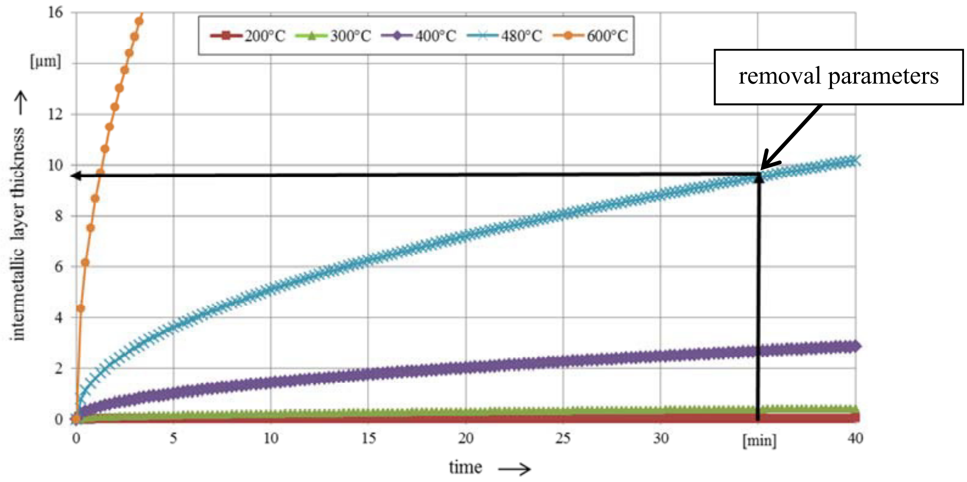

Fig. 3. Intermetallic layer thickness at different annealing temperatures in manufacturing process of roll claddings; T = 480 °C, t = 35 min.

The comparison of the analytically calculated intermetallic layer thickness of the roll cladding is confirmed by results measured at three positions in three cross sections with an extent of 11.4 ± 0.8 µm, which can be seen in Figure 4.

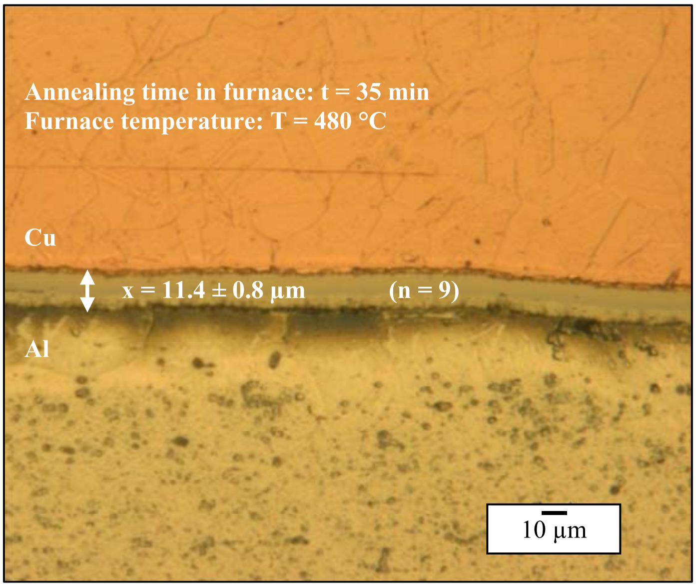

Fig. 4. Measurement of intermetallic layer thickness in cross section after roll cladding (T = 450 °C; t = 35 min.).

Based on the correlation between analytical calculation and measurements in cross sections, the additional growth of intermetallic phases in the cladding interface during laser beam welding can be calculated by (1) and (2). In order to estimate the thermal load of the intermetallic layer, numerical simulation is used. The validation of the numerical model is performed by fillet copper welding process, wherein the process parameters enable a heat input, which is sufficient to melt the aluminum at the cladding interface. Those parameters are used for simulation, wherein the resulting heat distribution, which is shown in Fig. 5, is calculated.

a)

b)

c)

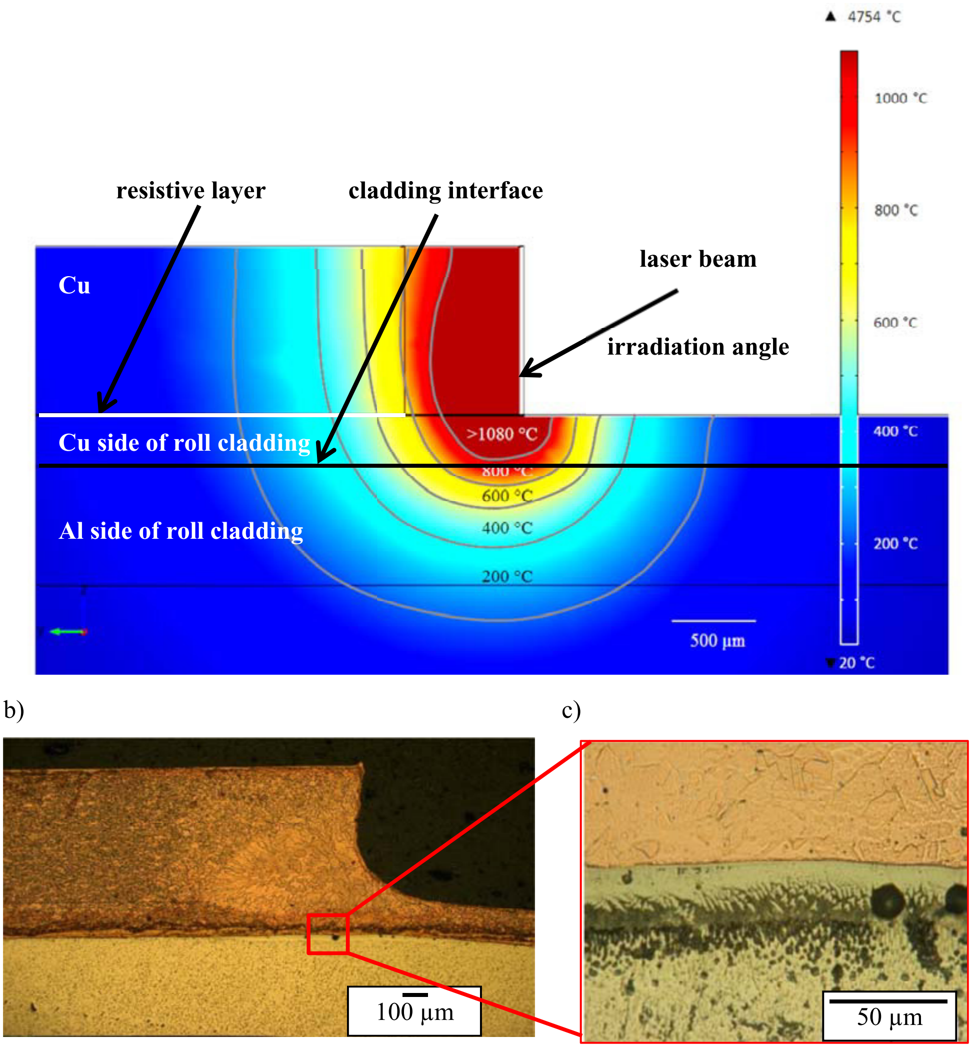

Fig. 5. a) Heat distribution in cross section with temperature > 660 °C in the aluminum cladding interface; b) cross section with molten aluminum in the cladding interface; c) detail of intermetallic phases in cladding interface.

The simulated temperature in the cladding interface exceeds 660 °C (Figure 5a), which induces the melting of aluminum. The occurrence of oxygen pores in cross sections (Figure 5b and c) and the significantly increased thickness of the intermetallic phases are an evidence of molten aluminum. This leads to the validation of the numerical model. In order to determine the maximal intermetallic phase growth, the upper limit of process window in laser beam welding, which was determined in the experiment, is used for analytical calculations. This upper temperature limit ($T_{M,Al}$ = 660 °C) should avoid the undesirable effect of melting aluminum in the cladding interface by heat conduction during welding. Figure 5 shows the correlation of intermetallic layer thickness and welding time at three different temperatures, calculated with formulas (1) and (2).

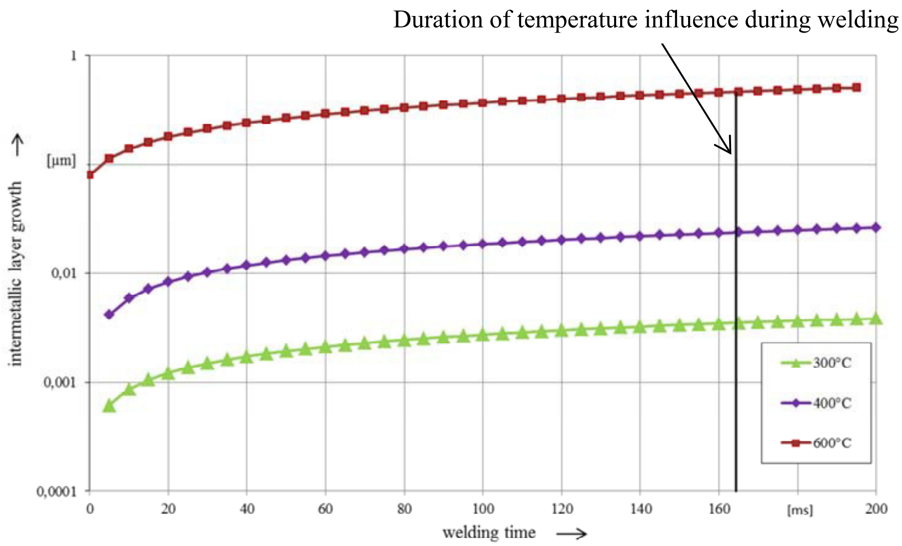

Fig. 6. Intermetallic layer growth in dependence of welding time based on heat conduction in dependence on different temperatures; welding parameter: P_L = 3.6 kW; v = 0.083 m/sec.

Welding speeds (v = 0.067…0.1 m/sec) and weld seam length of the experiments result in a process time is less than 200 ms. The maximal intermetallic phase growth of 1 µm, which is about 10 % of the original thickness can be seen as uncritical. In addition to the analytically calculated formation of intermetallic compounds in the diffusion layer near the weld seam, the intermetallic layer thickness was determined experimentally. The comparison between unwelded and welded cross section is shown in Figure 7a) and b), which shows again the validity of both analytical and numerical calculation. The increase of intermetallic phase thickness from 11.4 µm to 12.6 µm (10 %) does not indicate a critical decrease of mechanical and electrical properties.

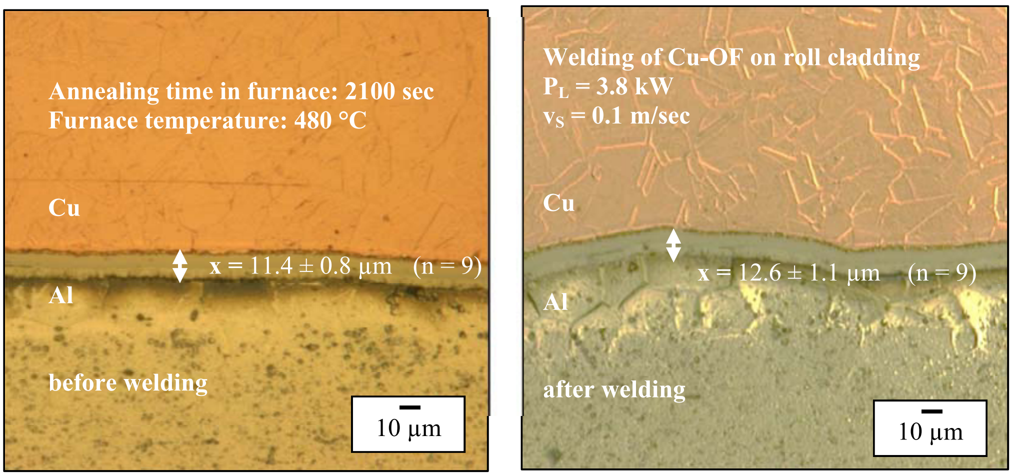

Fig. 7. Cross section of roll cladded interface a) before and b) after welding.

However, at wrong dimensioned thicknesses of roll cladded inserts (0.3 mm thickness of copper layer on roll cladding), the high thermal energy input, based on the required intensity for deep penetration at continuous wave welding processes can lead to an intermixture of both materials in the molten state and increased formation of intermetallic phases in the cladding interface. The high heat conductivity of copper ensures melting the aluminum in the cladding interface. Using a well dimensioned roll cladding (1 mm thickness), in order to reach a sufficient connection plane, the melting of the cladding interface can be avoided. Fig. 8 illustrate cross sections both without damage a) and with extensive intermetallic phase growth because of molten aluminum b).

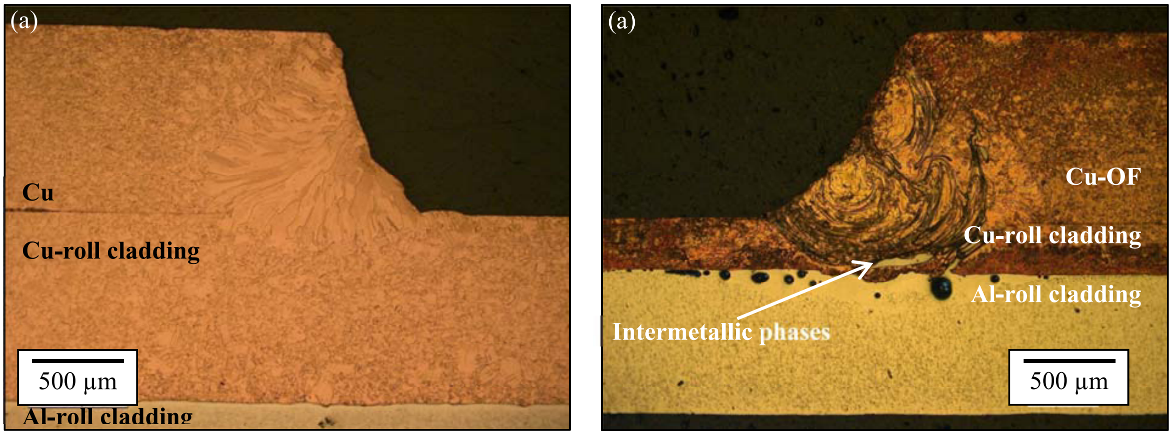

Fig. 8. a) Undamaged cladding interface in usage of 1.0 mm copper layer on the roll cladding; P_L = 3.8 kW; v = 0.1 m/sec; b) intermetallic phase formation in the cladding interface in usage of 0.3 mm copper layer on the roll cladding; P_L = 3.2 kW; v = 0.083 m/sec.

Due to the need of a certain welded cross section to provide sufficient mechanical and electrical properties of the copper-aluminum part, a minimum energy input is demanded. In order to avoid a thermal damage in the cladding interface (see figure Figure 8 b), a critical value for the cladding thickness is determined by an optimization loop in the numerical model.

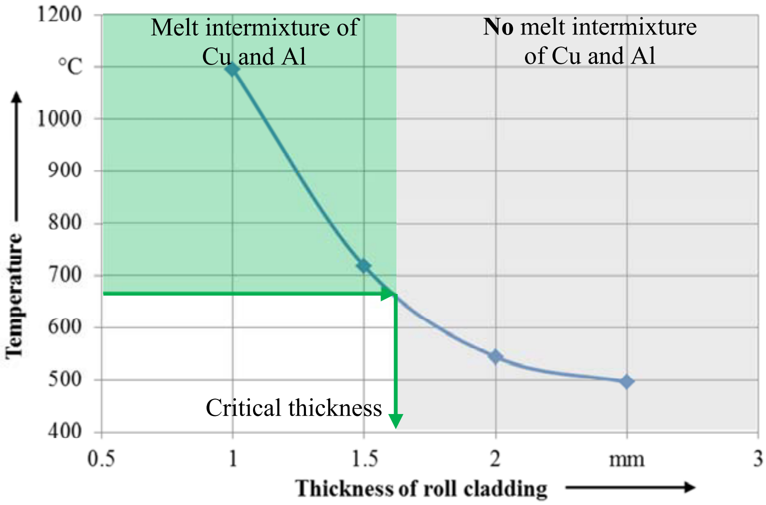

Fig. 9. Numerical data to optimize the total thickness of roll claddings (> 1.6 mm) without melting aluminum during welding PL = 3.5 kW; I = 3.9E+06 W/cm²; v = 0.083 m/s.

Figure 9 shows, that a thickness < 1,6 mm can avoid melting of aluminum during welding. Thus, a cost-benefit optimization of the roll cladding at constant material properties is achieved, to avoid unnecessary disbursements and weight for example in copper-aluminum connections of the electronic industry.

By using the numerical calculation to avoid the direct melt intermixture in the cladding interface, the rapid intermetallic phase formation can be avoided. Despite the melting of aluminum, induced by heat conduction has to be considered, that long term stable copper-aluminum connections are achievable.

4. Conclusion

The investigations presented in this paper show analytical and experimental results regarding intermetallic phase growth during heat input both at the roll cladding process and the subsequent welding processes. Based on the results of thermal simulation, the temperature in the roll cladding interface has been determined, in order to calculate the growth of the intermetallic phases. An agreement between the thickness of the phases in the analytical calculation and the experiment has been achieved. In consideration of high welding speeds, the energy input is limited whereby an uncritical growth in intermetallic phases of about 10 % was measured. Furthermore the prevention of damage in the roll cladding interface by means of unadapted material thicknesses or welding parameters can be assessed analytically and numerically. Despite the avoidance of copper-aluminum stirring in the solid state, wrong process parameters can lead to a melting of aluminum in the roll cladding interface, because of heat conduction and the forming of intermetallic phases. The simulation determines the critical thickness of the roll cladding to avoid damage like exceeding growth of intermetallic phases at preexisting welding parameters.

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